NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Continuum MAGAZINE

Clean Energy Innovation at NREL

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The NREL Spectrum of Clean Energy Innovation

NREL Leads Wind Farm Modeling Research

Driving Solar Innovations from Laboratory to Marketplace

Reaping a Harvest of Hope

NREL is a national laboratory of the U.S. Department of Energy,
Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Dan Says

Innovation Across the Clean Energy Spectrum

Visitors touring the National Renewable Energy Laboratory (NREL) are often amazed at the scope of our research and the depth of our engagement with private industry.

From our humble beginnings 35 years ago as the Solar Energy Research Institute, today NREL pursues research across a broad range of renewable energy and energy efficiency sources. As our scientific exploration expanded, so did our effort to develop, test, and validate new technologies. We began collaborating with private industry, from small entrepreneurial companies to large established businesses, to commercialize our scientific breakthroughs and to help them achieve production-ready products and manufacturing processes. This "market-relevant" research required an in-depth understanding of the factors affecting market adoption, leading to the development of a distinctive NREL competency in strategic energy analysis.

By design, NREL plays a critical role across the spectrum of clean energy innovation.

This issue of *Continuum Magazine* illustrates the breadth of innovation at NREL, from our scientific exploration into more efficient solar-cell materials and complex wind-farm computer modeling, to inventing a more efficient air conditioning system and helping a tornado-ravaged town rebuild using the latest sustainable energy and efficiency techniques.

As the nation's only national laboratory dedicated solely to renewable energy and efficiency, NREL acts as an innovation catalyst for private industry by reducing risk and encouraging private investment in promising new products and companies. Guiding new technologies from initial concept through commercial application requires comprehensive capabilities and expertise across the innovation spectrum, from fundamental science and market-relevant research to systems engineering and

Dr. Dan E. Arvizu, Laboratory Director

validation; and through commercialization and deployment.

Federal support to transform our nation's energy systems is critical because it is one of the greatest challenges facing our nation today, with market conditions unlike any other. Our nation's electrical grid, transportation, and fuel supply systems are highly regulated and largely constructed with technology developed more than 100 years ago. These challenges present significant barriers for new technologies and explain why private investment in energy-related research lags by a factor of ten to one compared to other major market segments such as pharmaceuticals and telecommunications.

This underscores the importance of the research we perform here at NREL, and of the public/private partnerships we enable. Our focus across the spectrum of clean-energy innovation ensures that new technologies move rapidly from the laboratory into the marketplace, delivering clean energy solutions to the nation.

Dr. Dan E. Arvizu
Laboratory Director
National Renewable Energy Laboratory

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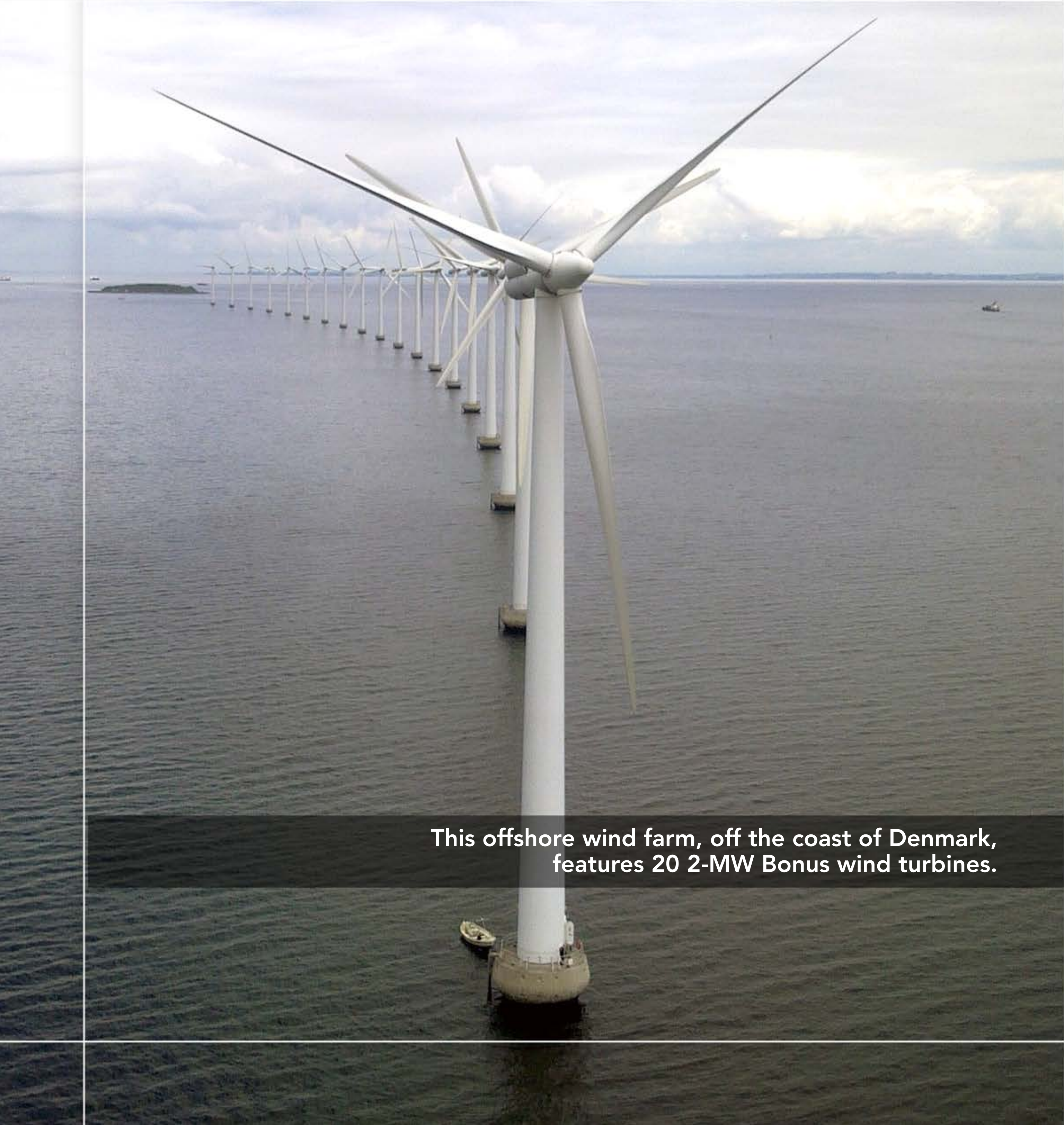
Issue 3

NREL Leads Wind Farm **Modeling Research**



This offshore wind farm, off the coast of Denmark, features 20 2-MW Bonus wind turbines.

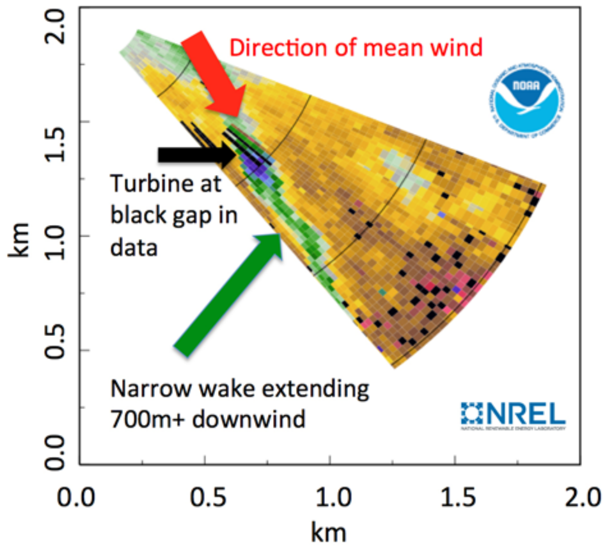
Researchers study the atmosphere surrounding large turbines to optimize performance.

The Tehachapi Pass Wind Farm, located in California, has nearly 5,000 turbines, and can generate 705-MW of wind energy.

Wind turbines can be greedy because individual machines are designed to gobble up as much wind energy as possible. Until recently, that was considered normal. Now, however, most turbines are built to be used in wind farms, and a single turbine's performance matters far less than the farm's overall efficiency. To address this new paradigm, the National Renewable Energy Laboratory (NREL) has created complex computer modeling tools to improve wind turbine design and overall wind farm performance, based on the best possible research data.

To that end, starting in 2011, NREL and the Renewable and Sustainable Energy Institute (RASEI) partnered with scientific institutions to conduct a complex study to understand atmospheric turbulence and turbine wake behavior. NREL and RASEI worked directly with:

- National Oceanic and Atmospheric Administration
- University of Colorado, Boulder
- Lawrence Livermore National Laboratory.



This high-resolution Doppler LIDAR scan shows radial wind velocities in the vicinity of a wind turbine, with cooler colors indicating lower velocities in the wind turbine wake.

A multi-organizational team of experts deployed precise instruments to create a detailed picture of the atmosphere surrounding large turbines. Among these instruments is the high-resolution Doppler LIDAR—a laser-based system that stands for "light detection and ranging." LIDAR scans can measure the wind speeds in a slice of air up to 1 kilometer (3,280 feet) from the ground and 6.9 kilometers (4.3 miles) long. In other scanning modes, it can focus on a single turbine and the area within 10 kilometers (6.2 miles) of it to observe the turbine's wake near the surface. For this study, researchers focused on a 2.3-megawatt turbine that rises almost 100 meters (328 feet) from its base to its hub. This research produced the first ever three-dimensional portrait of atmospheric activity surrounding a multi-megawatt wind turbine.

In addition to its work with Doppler LIDAR, the interagency team employed other high-resolution atmospheric instrumentation. NREL scientists gathered wind and turbulence data using commercial scientific platforms, including a specialized laser called a Windcube LIDAR and a sonic detection and ranging (SODAR) system, the Second Wind Triton. While LIDAR focuses on light bouncing off of particles in the atmosphere to measure wind speed, SODAR measures sound waves bouncing off of density fluctuations in the atmosphere. One beam of light or sound measures one direction, so three beams are needed to measure all three directions in space—up/down, forward/backward, and side/side. The researchers also installed high-frequency sonic anemometers on two new 440-foot meteorological towers to further supplement the data. Each of these instruments provided essential information to understand the dynamic inflow and turbine wake system.

Computing the Complex Nature of Wind Turbine Wakes

By their nature, wakes are complicated. Fluctuations in air temperature throughout the day can affect wind turbine wakes, so it's important to observe them in detail and understand how to minimize their impacts, according to Julie Lundquist, professor of atmospheric and oceanic sciences at the University of Colorado and a joint appointee at NREL.

Drawing on Lundquist's findings, NREL researchers are now implementing a Dynamic Wake Meandering model to simulate airflow through a wind farm. They wanted to compare the results they were collecting from their high performance computing model to this lower fidelity model as well as to more standard, basic industry models.

Unlike most wind energy industry teams, NREL investigators have access to high performance computing, including RedMesa, NREL's most powerful high-performance computing system. This system has a peak computational capability of about 180 teraFLOPS, which means it can perform 180 trillion "FLOPS," or floating point operations, per second. In the past, this sort of high performance modeling has not typically been available for creating industry wind models.

"We've been able to see what the differences are, and ask, 'Do we really need more complicated models, or can we just improve more simple ones?'," said Pat Moriarty of the NREL-based National Wind Technology Center.

For the multi-agency research project, this high performance computing is invaluable. In order to study offshore wind farms, NREL gathered wind plant data from Lillgrund Wind Farm, located off the coast of southern Sweden. Moriarty, along with NREL teammates Sang Lee and Matthew Churchfield, was able to simulate wind velocity, turbulence, kinetic energy, and time-averaged power output of a wind plant.


John Michalakes, Pat Moriarty, Julie Lundquist, Sang Lee, and Matt Churchfield conduct wind farm research at NREL's National Wind Technology Center.

They have also successfully calculated the relative impact of wake and atmospheric turbulence on wind turbine structural loading. This was the basis for a computational model that will simulate wind turbine arrays. The group expects to conduct another such study next year for a wind farm off the coast of the Netherlands.

To ensure accuracy, their results must be compared with actual observations. To carry that out, NREL and the Centro Nacional de Energías Renovables (CENER) in Spain are leading an international collaboration through the International Energy Agency to gather data from researchers and operating wind farm owners, and to benchmark existing simulation tools.

Dual Purposes of the Research

Overall, this ongoing research has two basic purposes:

The first is to understand the physics of local airflow, including how airflow changes in a wind farm, and how turbines interact with each other and the atmosphere. This is key because as turbines grow in size—approximately doubling in height over the past five years alone—they present more complex problems to wind turbine designers and operators.

A second purpose, Moriarty said, is that new insights from models can improve wind farm layout and operations. Based on the findings in the study, a wind project designer may want wider spaces between turbines to enable the farm to reap more energy. Also, after building a wind farm, an operator can design and implement a wind farm control system to fine-tune efficiency gains. This is becoming a cutting-edge concept in the wind farm industry.

As Moriarty explained, control systems were traditionally designed around single turbines—such as the above-mentioned wind gluttons. These designs allowed each turbine to optimize its own energy capture and minimize any wind damage to its structure. Using wind farm control systems, turbines also "know" about surrounding turbines. This technology can coordinate turbines to allow the maximum efficiency for a renewable energy project. For example, a front row of turbines may be tilted a certain direction in order to let more wind pass through so that a stronger airflow hits downstream turbines. As a result, each lone turbine may not capture the most energy, but the wind farm as a whole is capturing more energy. That's the eventual goal of these sorts of optimization tools, Moriarty said.

Leading a Worldwide Effort in Airflow Simulation for Wind Farms

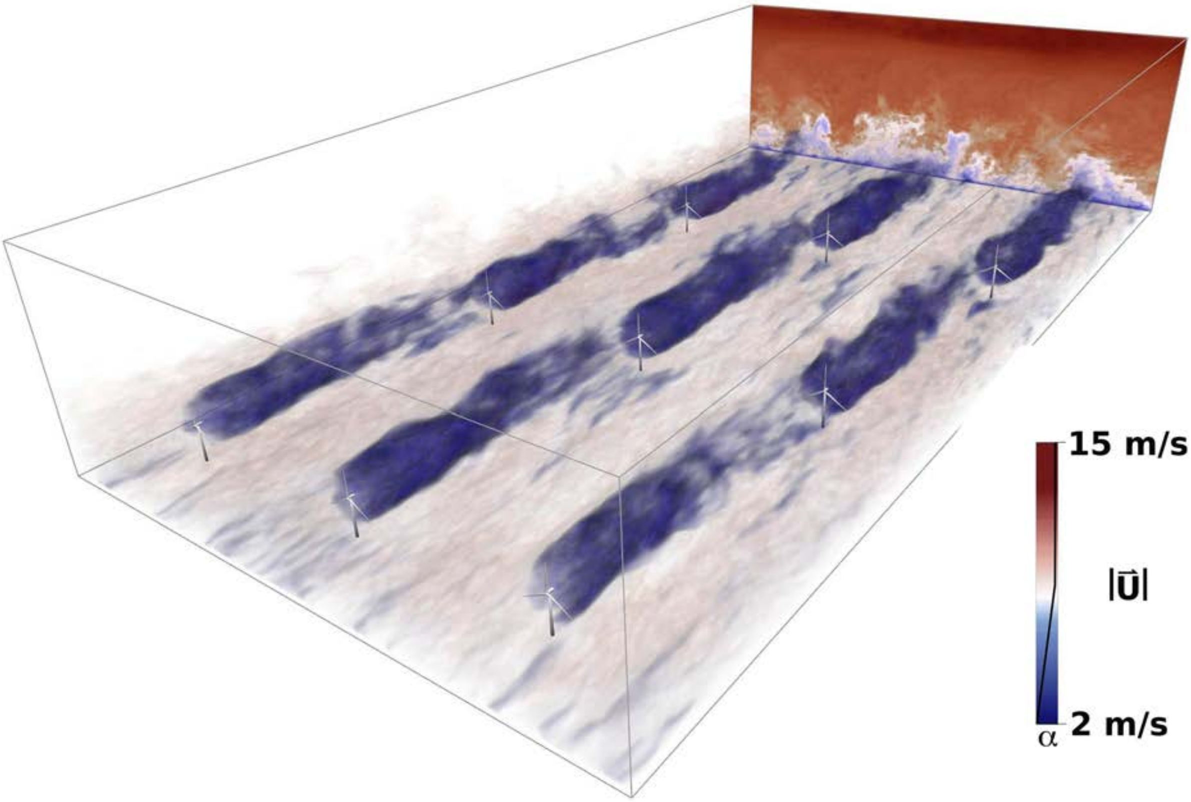
The timing is right for this pioneering research. Today, even though industry is increasingly interested in the large potential payoff from using these new techniques, there are relatively few groups around the world looking into wake models and testing airflow in simulation. One of the more intriguing innovations is the "wake steering method," which uses a control system to reconfigure a turbine's orientation and thereby guide the downstream wakes. This technique works without reconfiguring the massive wind towers. "Nothing else is changing—and you're getting free energy because of that," Moriarty said.

Efficiency gains can make a big economic impact. Field studies in Europe have shown an estimated 2% efficiency improvement with the wake steering method. However, these techniques are so new, the studies haven't been fleshed out yet. Moriarty said, "Probably the most you can gain in efficiency will be about 10%, but even 1% over the lifetime of an average wind farm is still $20 million."

NREL publicly released its latest wind farm modeling tool in January 2012, and held a webinar in May, which was attended by about 100 wind energy stakeholders worldwide. The new tool is already proving popular, and there have been several hundred downloads of the airflow simulation tool. Not only is this going to academia, but industry—manufacturers, wind farm developers, and consulting groups—are taking advantage of this offering as well.

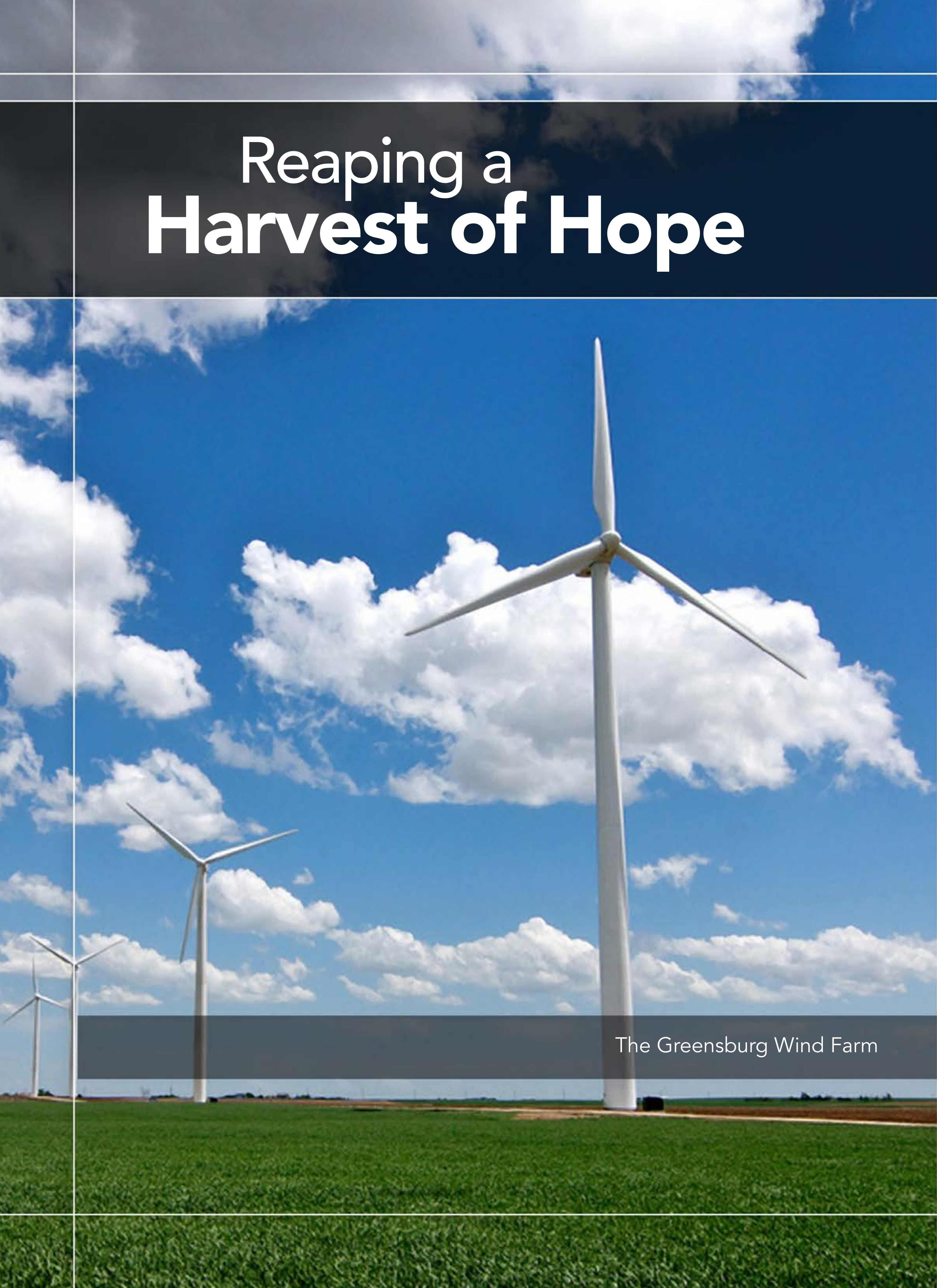
And this acceptance is expected to grow. In November 2012, NREL will host the International Wakebench meeting for International Energy Agency Task 31. Sixty groups from around the world are expected to attend, and NREL researchers will showcase their models and findings. "We are one of the world leaders in the topic right now—it's a big topic of interest in general," Moriarty said.

—Ernie Tucker



A computer model image of the downstream wakes on a wind farm.

Reaping a Harvest of Hope



The Greensburg Wind Farm

Five years after a devastating tornado, Greensburg, Kansas, has new energy and a new outlook.

On May 4, 2007, an EF-5 tornado—the highest rating of tornados—tore through Greensburg, Kansas, destroying or damaging more than 90% of the town's homes and businesses. With the help of many partners, including the U.S. Department of Energy and NREL, townspeople devised a plan to rebuild as a model green community.

On May 4, 2007, an epic tornado tore through Greensburg, Kansas, killing 11 people and leveling 90% of the town.

With Greensburg's municipal infrastructure in shambles, city leaders were tasked with jump-starting the entire town. Among their top priorities was restoring power so the recovery effort could begin in earnest.

Greensburg Citizens Champion Green Approach

A handful of citizens and business leaders championed a green approach to re-energizing their town—one that would tap in to Greensburg's abundant wind resource. However, city leaders lacked the experience and knowledge needed to pursue community-scale wind, and they had strong ties to the local power company that had served Greensburg for years and helped restore partial power immediately after the storm.

When a team of NREL technical experts arrived a month after the tornado, the city was close to finalizing a long-term deal with its traditional coal-based power provider to supply electricity to Greensburg. Although city leaders were torn between their loyalty to long-standing business relationships and their desire to go green, the NREL team encouraged them to explore wind energy in greater depth.

"In the Midwest, business is done based on who you know, who you've done business with for a long time, and what has worked well in the past," explained NREL Integrated Deployment Project Lead Lynn Billman. "In south-central Kansas, utilities had provided reliable coal-fired power for as long as most folks could remember. On the other hand, NREL had resources and economic data suggesting Greensburg could leverage its vast wind resource to not only meet its future energy needs but also demonstrate leadership and success on the clean energy front."

NREL presented a solid case for "pausing, taking a deep breath, and taking the time to weigh all of the options before moving forward," said Billman. With that in mind, the city opted for a short-term power purchase agreement (PPA) with its traditional power provider, which bought it time to fully assess the technical and economic feasibility of adopting community-scale wind as an alternative to fossil fuel. This enabled the community to move forward with the recovery process while allowing time to develop a vision of a sustainable, green energy future for Greensburg.

Initially, the vision was fragmented and lacked clarity. Greensburg city leaders were not energy experts, and neither were the other federal agencies that were involved in the recovery effort. Fortunately, NREL brought a 30-plus-year history of scientific discovery and clean energy innovation and deployment to the table. With its deep industry knowledge and wealth of practical experience in moving renewable energy technologies from concept to commercial application, NREL was uniquely positioned to help city leaders connect the dots.

By providing objective data, modeling, analysis, and tools that helped guide decisions about energy choices, policy options, and investments, NREL experts helped city leaders develop a comprehensive energy plan centered on cost-effective, high-efficiency buildings and community-scale wind. Taking an integrated approach to implementing energy

NREL's Integrated Deployment model has provided a framework for planning and implementing clean energy projects and initiatives in these locations nationally, and around the world.

efficiency and renewable energy technologies, they helped the city draft an energy road map that not only aligned with national energy diversity and reliability goals, but also became a model that other communities could replicate if facing a similar crisis. It was not easy to develop; nor would it be quick to implement. But the road map provided city leaders with the objective and realistic guidance they needed to put Greensburg on a clear path to a sustainable recovery.

Planting the Seeds for a Green Future

With additional input from citizens and various private sector and government entities, the Kansas City, Missouri-based community planning and architectural firm BNIM developed a Sustainable Comprehensive Master Plan. The plan outlined some specific long-term energy supply goals that would advance the community's collective vision and plant the seeds for future green growth. These goals included:

- Offering Greensburg-area customers 100% renewable source energy
- Maintaining the consumer rates at or near the current rate despite nationwide increases in fuel and energy costs
- Implementing a system that could be maintained by current city staff
- Defining a system and strategy that would be replicable in other Kansas communities.

In addition to providing the community with long-term, clean, economical power, these goals were designed to put Greensburg on the map as a pioneer in clean energy technology adoption. City leaders hoped that by harnessing the wind that almost destroyed their community, they'd be able to create economic development opportunities and provide a model other communities could replicate.

Harvesting the Wind to Fuel Opportunity

Kansas has the third-highest potential for wind energy of any state—a fact that is readily apparent to anyone who spends a typical day in Greensburg. While early NREL technical assessments confirmed the town's class 5 wind resource, NREL continued its detailed study and analysis to provide the bankable data necessary to attract developers.

City leaders asked NREL to identify potential sites for a city-owned wind farm and conduct detailed computer modeling and site measurements. The city also relied on NREL's life-cycle cost analysis

Beyond Greensburg: NREL's Integrated Deployment Model Provides a Framework for Community Energy Planning

NREL's work in Greensburg, Kansas, is just one of several projects in which the lab's technical experts apply a comprehensive, holistic approach to deploying energy efficiency and renewable energy technologies. NREL's Integrated Deployment model provides a framework to focus on the national goal of accelerating market adoption of clean energy technologies through local efforts, and it is scalable and replicable around the world.

NREL Integrated Deployment projects have facilitated energy planning efforts in several communities, cities, states, and international locations. Each project was launched in response to unique opportunities (concentrated rebuilding in New Orleans, 100% green rebuilding goal in Greensburg, Kansas); adverse economic circumstances ($.50/kilowatt hour (kWh) electricity rates in Hawaii, $1.00/kWh in Alaskan villages); or mission-related concerns (energy security and reliability issues for the U.S. Department of Defense, pollution impacts for National Science Foundation polar research).

"These projects represent a broad spectrum of locations, circumstances, and issues," said NREL Integrated Deployment Lab Program Manager Mary Werner, "but all reflect examples of successful implementation of the Integrated Deployment model that can be replicated across the country and globe."

and its extensive energy project development and financing experience to draw up business plans demonstrating how wind energy could be successful for a small municipal utility.

As evidence of a wind farm's viability mounted, NREL facilitated meetings between the city and its long-term power provider, identified potential alternative power purchasers, and ultimately brokered a deal that would enable Greensburg to realize its vision of meeting its energy needs with clean, green, homegrown power.

In April 2009, the City of Greensburg entered into a PPA with Kansas Power Pool, a green power provider that promised "100% renewable electricity, 100% of the time." With a blueprint in hand, the City of Greensburg and Kansas Power Pool, in collaboration with the U.S. Department of Agriculture and John Deere Renewable Energy, set out to build a 12-megawatt (MW) wind energy system designed to meet the pre-tornado energy needs of the community. NativeEnergy, which helped finance the project, signed on to market the excess energy the wind farm produced as renewable energy credits (RECs).

"Blessed with a unique opportunity to create a strong community devoted to family, fostering business, [and] working together for future generations."

—Greensburg's vision statement from the Comprehensive Sustainable Master Plan

The Greensburg Wind Farm is comprised of 10 1.25-MW wind turbines, supplying a total of 12.5 MW of renewable wind power to the town.

The commitment to 100% wind energy, 100% of the time was a milestone for Greensburg—one that put green at the heart of the recovery effort and infused it with new energy and a new focus.

City officials were not alone in their desire to capitalize on Greensburg's abundant renewable resources. From the earliest phases of the recovery effort, progressive local businesses had sought ways to save energy and cut costs by putting energy innovation into action.

The local John Deere dealership, BTI-Greensburg, was among the first businesses to rebuild, and owners Mike and Kelly Estes were frontrunners in

The BTI-Greensburg John Deere dealership in Greensburg includes two on-site wind turbines that provide electricity to the facility.

going green. "When you have a chance to build back from scratch, you look for a new and better way," said Mike Estes of the dealership's decision to incorporate green features, including wind turbines, into the design of its new LEED Platinum-rated building. To enable local distributed renewable energy system owners such as BTI-Greensburg to reap the greatest return on their investments, NREL policy analysts assisted the city, which operates the municipal utility, in developing safety and reliability ordinances, a net-metering policy, an interconnection agreement, and solar and wind ordinances.

The Estes brothers, who own four John Deere dealerships throughout Kansas, were so impressed with the quality and performance of the Endurance wind turbines they purchased for their new facility that they opted to enter the wind business themselves. During their business planning process, they sent teams to NREL's laboratory in Golden, Colorado, to discuss the wind industry. BTI Inc. launched its wind turbine subsidiary, BTI Wind Energy, in 2008.

That same year, BTI Wind Energy formed the Harvest The Wind Network (HTWN) of dealers to sell, service, and support wind energy products across North America. The independent dealer groups that composed the network each had dedicated wind specialists and technicians who were trained and supported by HTWN. Participants in the network partnered with local community colleges to provide turnkey wind energy solutions to local businesses, homes, schools, and hospitals. By successfully implementing wind energy systems ranging from residential systems to community wind projects, HTWN sought to extend the economic benefits of wind energy to communities throughout the United States and Canada.

Signs of Growth

Over time, signs of healing began to surface in Greensburg. By 2010, the completion of Greensburg's 12.5-MW wind farm, the growth of BTI Wind Energy's HTWN, and successful green building projects such as the LEED Platinum-rated Kiowa County Memorial Hospital, the SunChips® Business Incubator, City Hall, and Prairie Pointe Townhomes garnered national attention, engendered community pride, and offered tangible evidence that the town was on the path to recovery. Most importantly, these early successes helped cultivate a collective sense of hope for the town's future.

Reaping What They Sowed

Five years after the tornado left a 22-mile path of destruction where Greensburg had once been, the town has emerged from the rubble with a new energy and a new outlook for the future that are firmly rooted in the community's vision of embracing sustainability and clean energy.

Today, the Midwestern wind that nearly destroyed the town is being harnessed to power its recovery. The Greensburg wind farm on the outskirts of town generates enough energy to power 4,000 homes—more than enough clean, renewable electricity to supply Greensburg and several other communities in the power pool. The excess power is placed back on the grid and marketed by Native Energy Inc. to other customers in the form of RECs. In 2011, Greensburg's significant contributions to the cleantech industry received international recognition when its municipal wind farm was named Wind Project of the Year by Renewable Energy World.

"I think about Greensburg, Kansas, a town that was completely destroyed by a tornado but is being rebuilt by its residents, as a global example of how clean energy can power an entire community—how it can bring jobs and businesses to a place where piles of bricks and rubble once lay."

—President Barack Obama, 2009 State of the Union Address

Today, Greensburg is harvesting the wind to power its recovery. The 12.5 MW wind farm is visible on the horizon.

Through its Harvest the Wind Network, BTI has helped extend the opportunities for green growth beyond Greensburg's borders. HTWN has already installed 125 turbines nationwide, which are generating more than 5 MW of wind energy. In addition, it is developing more than 100 additional projects, each of which will be able to generate between 50 kW to 15 MW of wind energy.

By working with NREL to harness its most abundant renewable energy resource as part of a sustainable long-term recovery plan, Greensburg discovered great opportunity in the midst of great crisis. Today this resilient heartland community, which was in decline before the storm hit, is reaping a healthy harvest of hope—one it is sharing with other communities that are either facing or preparing for similar crises. "NREL has made our lives easier and better," said former city administrator Steve Hewitt. "Our experience will benefit many other communities that NREL will be working with."

From the beginning, the local nonprofit organization Greensburg GreenTown™ worked closely with NREL, introducing NREL experts to the people of Greensburg, and working with lab representatives to deepen GreenTown's understanding of energy solutions. That partnership has borne fruit well beyond the borders of Greensburg. Residents of Joplin, Missouri, turned to Greensburg for recovery assistance after an EF-5 tornado struck their town on May 22, 2011. As a result, Greensburg GreenTown launched its second field office to help Joplin recover as sustainably as possible and serve as a model for other communities. GreenTown is using a myriad of NREL-developed outreach and technical documents in its work to educate and inspire people in Joplin and other communities toward a greener future.

In 2009, Greensburg leaders served as Eco-partners to a city in Sichuan Province, China, to help it recover from an earthquake. In addition, representatives from Japan are working with NREL to plan a visit to Greensburg and to identify best practices and lessons learned that they can apply to their efforts to rebuild after the 2011 tsunami.

As Greensburg's residents, businesses, and institutions press forward on their new, sustainable path, the benefits of going green are beginning to hit home. Home and business owners boast about their lower energy bills. Businesses with a sustainability mission are exploring Greensburg for possible expansion. Eco-tourism and other small businesses are emerging. Young people are looking to return home and settle down after college. As the recovery progresses and Greensburg's future continues to unfold, hope continues to grow.

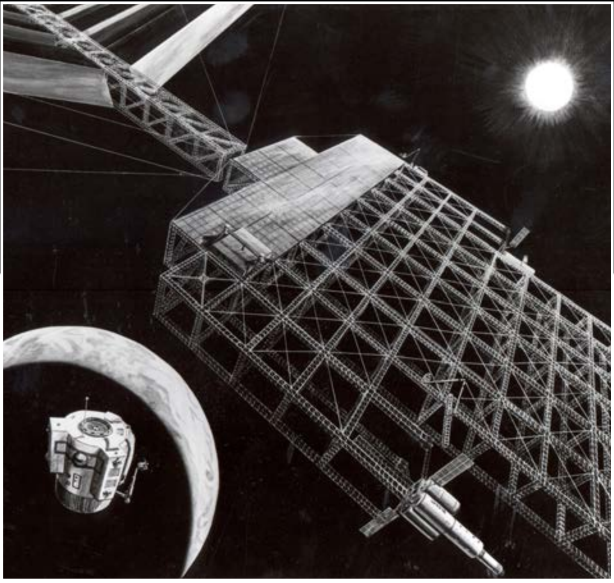
Meanwhile, Greensburg has emerged as a world model of sustainability, offering an inspiring example of what is possible when the people of a community and the government come together with common purpose. "We've been blessed with opportunity here," said Mayor Bob Dixson, "and we have a tremendous obligation to offer hope to the world."

—Karen Petersen

Driving Solar Innovations from Laboratory to Marketplace

NREL's partnership with a number of thin-film PV companies has supported tremendous growth in the industry.

Disruptive innovation is making solar cost competitive with non-renewable energy.



The success of Bell Laboratory's solar-powered satellite technology provided a foundation for worldwide commercialization.

Few would have thought in the 1970s that U.S. military-funded core technologies would someday lead to the internet. Or that a solar photovoltaics (PV)-powered satellite would give rise to the technology that powers all of our modern wireless communications. The idea of transferring technology from laboratory to market is nothing new.

As a U.S. Department of Energy (DOE)-funded renewable energy research laboratory, the National Renewable Energy Laboratory (NREL) serves a unique role of developing promising technologies past the high-risk stage of nascent research, to the point where private companies can take them to market.

"Most companies cannot invest in research that could be a decade away from a commercial product," said Bill Farris, NREL's Associate Laboratory Director of the Innovation Partnering and Outreach Directorate. "We have the facilities and the expertise to address the fundamental scientific questions and to accelerate the pace of these innovations—but it takes commercial partners to build the concepts at a manufacturing scale."

Accelerating the pace of transfer from lab to marketplace is a key component of DOE's SunShot initiative, which aims to make solar power cost competitive with traditional sources of electricity by the year 2020. With several trillion dollars at stake worldwide, SunShot aims to strengthen the United States' position in the global clean energy race, fostering competition among the most promising innovators and technologies.

Since its early beginnings, PV has grown to be a serious contender among the world's sources of electricity with a steady evolution that has raised efficiencies and reduced system costs. But to compete with entrenched and commoditized incumbents, it must find more disruptive, or groundbreaking, advancements while weathering an economy that has challenged investment and manufacturing.

The Clean Energy Race

In the 35 years since its inception as the Solar Energy Research Institute, NREL has gained worldwide recognition for its work addressing the challenges unique to the energy sector. Its solar research has yielded 34 solar cell conversion efficiency records, 153 issued patents, and thousands of contributions to peer-reviewed science journals. The laboratory has also driven key discoveries in solar cell materials, devices, fabrication, characterization, and production.

By performing basic research and development (R&D), NREL works to bridge the energy sector's first unique barrier, known as the "technological valley of death." This is the phase when investments in time and capital are needed to prove the market viability of a promising technology. NREL also helps bridge the later barrier, known as the "commercialization valley of death," by supporting industry partners in scaling up technology to attract private funding for manufacturing.

Farris likened the clean energy race to the Olympic 4 x 100 sprint relay—the transfer of baton from one runner to the next is a brief but critical part of the race. "For several meters, the two race hand in hand, but there has to be a well-executed handoff. We establish the momentum, but the commercialization partners have to finish the race,

An early prototype of a cadmium telluride film module developed by NREL and Golden Photon in 1991.

and they ultimately do the work of building a business around the technology."

A Progression of Technologies

Throughout the lab, scientists and business staff alike are eager to see their technologies leave the nest. The technologies are not pitted against each other, but instead, progress on different tracks depending on their maturity. Technologies considered to be evolutionary, such as crystalline silicon (Si), comprise most of today's PV. For the past several decades, NREL has also advanced second-generation technologies such as thin-films made from amorphous silicon (a-Si), copper, indium, gallium, and diselenide (CIGS), or cadmium telluride (CdTe). These technologies have the potential to be disruptive—that is, with continued improvements to cost and efficiency, they could help meet our energy needs and targets over the next five to ten years, or beyond. These types of changes are much like going from corded telephones to wireless cell phones or from laptop computers to tablets.

NREL also advances high-efficiency III-V multijunction technologies, including inverted metamorphic multijunction (IMM) cells that have the potential to bring revolutionary changes in the more distant future. Changes of this magnitude are akin to moving from megahertz computer processors to gigahertz processors.

NREL's Innovation Spectrum at Work

Among NREL's many innovations, one that demonstrates the lab's proficiency in transferring technology from research through commercialization and into large-scale deployment is cadmium telluride (CdTe). Thin film technology is highly valued by private investors because it uses less semiconductor material than silicon solar cells and can also be quickly deposited onto various glass, metallic, or even plastic substrates, providing both cost and production advantages.

When the project started in 1990, CdTe was considered suitable for thin-film PV because it was a semiconductor with a band gap of around 1.5 eV, which closely matches the terrestrial solar spectrum for optimum conversion efficiency. This meant that it could absorb more of the spectrum of the sun's energy, which allowed it to convert more than 10% of the sun's energy to electricity—a threshold that made it attractive to explore for manufacturing.

In 1991, NREL and Golden Photon earned a prestigious R&D 100 Award from Research and Development (R&D) Magazine for the development of a CdTe PV module manufacturing process. Over the next several years, NREL's collaborations with the industry to further develop CdTe seeded technology and process improvements alike.

"In the early years, our primary goal was to understand all the roadblocks the industry was encountering," said Principal Scientist Tim Gessert. "We visited the sites to learn about the challenges and there were many first meetings. Sometimes, we would simply help the companies understand what kinds of skills and expertise they needed to bring onboard."

By 1996, Golden Photon was able to provide the U.S. Navy with a 25-kW array of CdTe modules, which at the time was the largest CdTe array in the world. Another early partner, Solar Cells, Inc., proved a thin-film cost structure that gave rise to more than a dozen start-up thin-film PV companies. This ultimately led to the creation of First Solar LLC, a leading worldwide PV manufacturer that uses CdTe technology optimized at NREL.

In 2003, First Solar installed CdTe modules at NREL's Outdoor Test Facility for long-term, outdoor performance monitoring. The company also enlisted NREL's deposition expertise to aid their efforts to improve light transmission into the electrical junction, thereby forming lower cost and higher efficiency thin-film modules.

How Do You Measure Industry Impact?

As part of the "Startup America" initiative supporting high growth entrepreneurship, President Obama in 2011 issued a directive to foster innovation by increasing the rate of technology transfer and the economic and societal impact from federal R&D investments.

In 2009, NREL began working to spur clean energy entrepreneurship by increasing the number of CRADAs, patents, licensing transactions, rewards to inventors, and innovations transferred to the private sector. NREL's innovative output increased dramatically and in 2011 alone NREL generated 134 invention records, 55 filed U.S. patents, 16 issued patents, and 21 royalty-bearing commercial licenses. NREL's solar research portfolio represents approximately a third of the laboratory's overall inventions and more than half of its commercial licenses.

Together, NREL and First Solar developed a unique process for manufacturing high-efficiency thin-film CdTe cells on low-cost commercial soda-lime glass. The process, which quickly deposits uniform layers of semiconductor material for photovoltaic (PV) modules, won a 2003 R&D100 Award and was considered a significant milestone in the race to produce cost-competitive solar energy.

NREL's research team also explored transparent conducting oxides (TCOs), which are doped metal oxides used as a front electrical contact in thin-film devices. By optimizing the light transmission through the TCOs, NREL was able to boost the cell efficiency to set a new CdTe cell efficiency record of 16.7%.

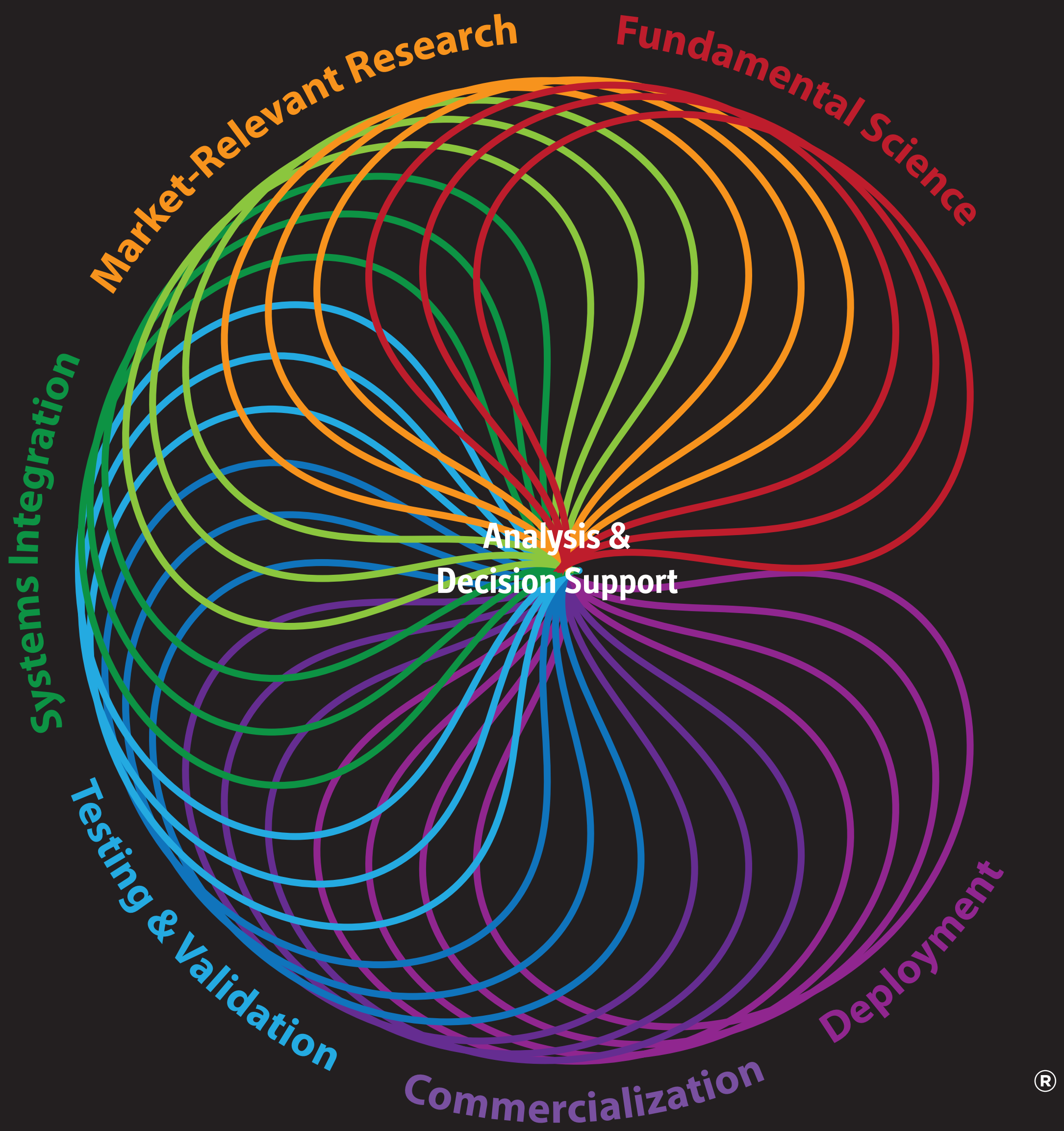
Commercialization and Deployment—Impacts on a Global Scale

CdTe's increasing cell efficiency was a large driver behind the formation of PrimeStar Solar, a company that participated in NREL's PV Technology Incubator program. In 2007, NREL signed a Cooperative Research and Development Agreement to allow PrimeStar to transition NREL's CdTe technology to commercial production and PrimeStar also received a $3 million incubator award to commercialize its low-cost PV panels. In 2011, PrimeStar was acquired by General Electric (GE), which had made large investments in the company since 2008. The acquisition accelerated the pace of commercialization and represented a key step in GE's plan to build a large-scale solar PV module plant in Colorado.

As it has matured, CdTe technology has achieved many additional milestones. First Solar has used the technology to produce 1 GW of PV modules in 2009, and more than 6 GW of modules to date. It also set world records for CdTe PV cell (17.3%) and PV module (14.4%) efficiency, all of which NREL has certified.

In 2012, First Solar installed its 10 millionth PV module in the 550 MW Desert Sunlight Solar Farm project in Riverside County, California. The project is part of a 2.7-GW pipeline of utility-scale projects in the U.S. and is expected to support 7,000 construction and supply chain jobs over several years. When completed in 2015, the project will be one of the two largest solar PV projects in the world.

Continued on page 18



The Spectrum of Clean Energy Innovation

For more than 30 years, the National Renewable Energy Laboratory (NREL) has advanced the science of renewable energy and energy-efficiency technologies while building the capabilities to guide rapid deployment of commercial applications. Transforming our energy systems to achieve the nation's aggressive economic, environmental, and security goals requires a comprehensive approach. Today, NREL is at the epicenter of this transformation–enabling a future of sustainable energy systems based on clean, cost-effective, and secure resources.

The scope of NREL's capabilities emulates the nature of the innovation process itself. Shepherding new technologies from initial concept to commercial application requires a breadth of expertise across the innovation spectrum, from fundamental science and market-relevant research to systems integration, testing and validation; and

Analysis and Decision Support: NREL's leadership role in clean energy analysis informs every stage of the innovation process.

Fundamental Science

NREL scientists focus on unlocking the secrets of energy-related physical and biological materials at the atomic and cellular levels–with the goal of discovering tomorrow's clean energy solutions. Renewable energy and efficiency research theory and experimentation encompass biomolecular, chemical, computational, and nanoscience; as well as optoelectronics, superconductivity, and solid-state physics.

Market-Relevant Research

NREL researchers couple scientific discovery with market need, focusing on next-generation technologies with the greatest potential for transformative solutions. Inventions resulting from NREL research reduce the cost and increase the performance and reliability of solar, wind, biomass, and geothermal systems; building and vehicle technologies; and manufacturing processes.

Systems Integration

To increase penetration of renewable energy and energy-efficiency technologies, NREL systems integration experts validate data and provide analysis and techniques to support deployment and integration into the existing energy infrastructure. NREL capabilities include the development of advanced vehicles and fuels, energy-efficient building design, systems modeling and simulation, and distributed energy testing and validation, including interconnection standards and controls.

Testing & Validation

Transitioning products rapidly from development into full production requires demonstrating and validating the performance of working prototypes and systems, and improving their reliability and operation.

NREL combines systems engineering, simulation models, and analysis with unique testing facilities to evaluate the performance of its own prototypes as well as those from private industry.

Commercialization

Sponsored research and development agreements and licenses with private industry are crucial to incorporating promising new technologies into cost-competitive products for the marketplace. NREL has a long history of close interaction with companies seeking to capitalize on its research to develop commercial products, from entrepreneurial clean energy start-ups to large multinational corporations.

Deployment

To catalyze the large-scale adoption of proven renewable energy and energy-efficiency products and technologies, NREL consults with standards organizations, utilities, builders, consumers, and state and federal agencies. NREL provides information and tools to help communities, industry, and government select the most impactful technologies to reduce their fossil energy use.

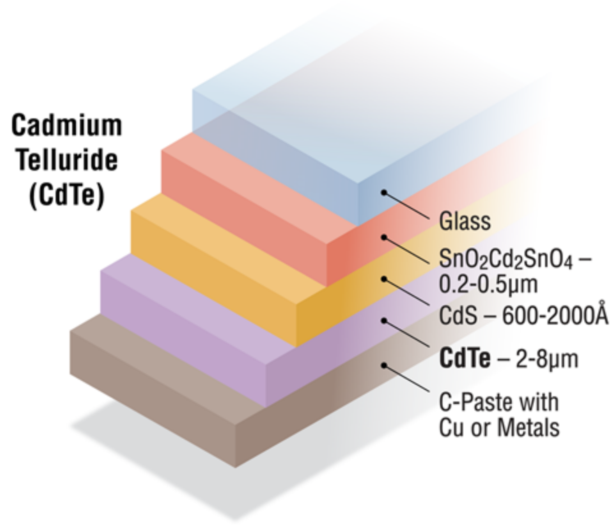
through commercialization and deployment. The process is interdependent and iterative, building upon itself and looping back for validation and refinement.

The NREL innovation spectrum is highly interactive within the laboratory and across other research institutions, and closely connected to private industry. Enabling close collaboration among scientists, analysts, policy makers, entrepreneurs, and venture capitalists results in market-relevant technologies and competitive clean energy products and services.

NREL provides the scientific and analytical leadership to guide the innovation process, while contributing its knowledge and expertise at each stage to accelerate adoption of renewable energy and energy-efficiency technologies and systems.

Fundamental Science—Getting Back to Basics

In some ways, cadmium telluride has been described as a victim of its early success. Gessert explained, "It showed its potential very early compared with other technologies, so most of the resources went to figuring out how to scale it up, rather than on its fundamental properties." At the same time production was increasing, laboratory cells found only incremental increases in conversion efficiency due to limits in the material's open circuit voltage and fill factor.



A CdTe thin-film PV device showing the layers that are deposited onto a glass superstrate that allows sunlight to enter.

In 2012, a DOE-sponsored NREL workshop convened industry, academia, and the national laboratories to discuss scientific research avenues for disruptively increasing CdTe efficiency toward a goal of 20% efficiency with processes and materials that can achieve the SunShot cost goal of less than $0.50 per watt.

Today, NREL's CdTe team, led by Principal Scientist and Thin-Film PV Group Manager Rommel Noufi, is leveraging years of thin-film PV materials and devices expertise to perform the research needed to understand the material's fundamental limitations on the solar cell performance. This research aims to identify the mechanisms that limit the open circuit voltage and fill factor of CdTe PV devices and advance new processes and device designs. By addressing existing limitations to enable dramatic increases in conversion efficiency, the team is undertaking the market-relevant research needed to help solve the challenges of today's thin-film PV manufacturing industry.

—Molly Riddell

A First Solar associate handles photovoltaic materials at the company's Ohio manufacturing plant.

Toward a Multi-Terawatt Future

The DOE SunShot Initiative's goal of reducing the installed cost of solar energy systems by 75% by the end of the decade calls for photovoltaics (PV) improvements in three main areas: solar-cell efficiencies, material processing costs, and scalability to terawatt (TW or 1012 W) levels.

According to the SunShot Vision Study the global PV market has grown at average annual rate of 53% over the past decade, with PV shipments reaching 17 gigawatts (GW) in 2010. Thin-film technologies are growing rapidly within this market, due to successes in reducing costs and advancing production.

With the rapid project growth comes the challenge of ensuring the glass industry can meet the increasing demand. Because glass is a key component of CdTe thin-film systems, NREL scientists have joined with large glass manufacturers to explore different glass compositions that may have ideal interactions with the chemical and electrical properties of the solar cells.

One large specialty glass manufacturer, Corning Inc., has called on NREL to analyze the thermal and diffusion properties of glass with multiple different compositions and the ways that chemicals diffuse differently into solar cells. "We've had a very productive CRADA with Corning," Principal Scientist Tim Gessert said. "They were interested in ways to tailor glass to PV applications, and through our ongoing work with them, we were able to demonstrate cells fabricated at the higher temperatures needed for PV."

While thin-film technologies currently comprise a very small percentage of the world's PV production, they have been growing at a rate of more than 35% each year. "Fast growth sneaks up on you," Gessert explained. "PV production is doubling every two years, and with this type of growth, by 2018, more than half of the glass made worldwide could go into a product that is just a blip on the chart today."

Reflecting on NREL's achievements in past decades and the amount of work left to do improving costs, efficiency, and processes to enable large-scale solar adoption across America, Gessert put the mission in an even larger context. "It took about 135 years to put the world's electricity infrastructure together. Replacing it in the next 35 years is no small task."

Energy Innovation Portal Bridging Information Gap

Hosted on the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) website, the Energy Innovation Portal—http://techportal.eere.energy.gov/—was created by NREL and has become the premier Web-based database for facilitating technology sourcing from multiple institutions through one access point.

Database revolutionizes intellectual property transfer from DOE's national laboratories to industry.

Call the Energy Innovation Portal (the Portal) a Craigslist for technology transfer, aimed at entrepreneurs, investors, and corporate technology scouts. Hosted on the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) website, this Web application created by the National Renewable Energy Laboratory (NREL) has rapidly grown into a cyber-marketplace, but instead of used bikes and weed whackers, users take advantage of cutting-edge clean tech.

Starting from the germ of an idea that was roughed out on a conference room whiteboard, the Portal has become the premier Web-based database for facilitating technology sourcing from multiple institutions through one access point.

The Portal, which includes more than 16,000 issued U.S. patents and published U.S. patent applications related to clean energy, has many successes already, including:

- 1,300 leads from "technology seekers"
- 18 separate transfers into the commercial marketplace
- 8,000 visitors each month.

Since its launch 24 months ago, the site has matured to the point where NASA and Sandia National Laboratories have adopted its architecture for their own tech transfer sites.

"The Energy Innovation Portal is designed for collaboration and partnership, and allows us to share innovations from our public-sector labs with private-sector business partners," said Bill Farris, NREL's Associate Laboratory Director of the Innovation Partnering and Outreach Directorate.

Finding the Path to a Tech Transfer Portal

As obvious and effective as that concept sounds now, the path wasn't always so clear. Farris first began pondering the prospect in 2008, his curiosity piqued by a single line of DOE's request for proposal to manage NREL. The document asked contractors, such as the Alliance for Sustainable Energy, what each would do to commercialize all EERE technology.

"Just that simple sentence got us thinking," Farris said. He and others in the Alliance leadership wondered, "How can we work with the other labs to assemble the intellectual property?"

Inter-lab competition was the rub. Prior to this request, the labs and intellectual property they produced were fragmented. For example, different labs might work independently on a similar solar technology, then each would seek to commercialize their own innovations. Something had to change for collaboration to begin.

"We saw an opportunity to make a difference for all of DOE, and reached out to peers at national labs," Farris explained.

The upside of bundling intellectual property was obvious. Each lab has hundreds—or in the case of bigger institutions, thousands—of patented technologies stemming from research and development, all at various stages of the licensing

The SkyTrough® parabolic trough solar concentrator uses ReflecTech® mirror film instead of glass mirror facets. This technology, which is featured on the Energy Innovation Portal, was first developed by ReflecTech, Inc. in collaboration with NREL, and was tested at NREL, as shown above in the left image. Today, the image on the right shows this technology at full commercial scale.

process. The national labs are eager to license their work because DOE has charged them with transferring early-stage and applied research to industry partners.

At the same time, outside the labs, technology-hungry investors are always looking for the latest clean tech breakthroughs. The problem was getting the two to meet. It turns out, the most effective solution was to create a virtual classified ad section, similar to what newspapers use to bring readers together.

Farris assembled a small team, beginning with Matt Ringer—a chemical engineer armed with an MBA—to begin evolving the vision. “I don’t know how we could have anticipated the way this would turn out when we began three and a half years ago,” said Ringer, who currently serves as NREL’s Commercialization Program manager.

The process started with careful outreach to the laboratories—outreach devised to dispel any perception that the Portal would function as merely an NREL site. Then the team members had to figure out what barriers might prevent seekers from accessing the patents.

“They know the national labs are out there, and potentially have technologies that might be relevant to business. But how would someone approach a laboratory?” Farris said. He also realized that if a curious entrepreneur did figure out an avenue into one lab, doing so wouldn’t provide clues to what might be on the shelves at the remaining national laboratories.

Developing a Web application seemed like a good route. Realizing they needed an ace at coding, Farris and Ringer turned to NREL’s Information Services management to hire developer Steve Jones, who had experience with start-ups. As Ringer said, it was one thing to sketch ideas on a whiteboard, but another thing entirely to get it into code and roll out a working site. Jones was an ideal fit, and the Portal began taking shape.

Helping Technology Seekers Make Contact

“It took some smarts on how to build a relationship. It took some smarts on how to build a good Web interface,” Farris said. “With EERE backing, we essentially created a referral engine.” In keeping with their sensitivity to the other labs, the team created a site on which each lab manages its own content. This is reflected in the 675 market summaries the labs have added, each of which gives more detail about a patent or patent group.

The benefits of this collaboration are clear. “If you’re a technology seeker, you gain direct access to the person at that laboratory who’s responsible for that technology,” Farris noted. After searching and finding something such as the latest in lithium batteries, a client can click on an available technology, fill out a form, and the Portal will send an email to the patent holder.

As a vote of confidence in the national site, NREL shut down its own site listing NREL’s license-ready technologies. The lab, which conducts 20 to 30 licensing transactions per year, is benefitting from the inclusivity. “We’ve seen great value ourselves,” Farris said.

Apparently, so have others. The site is currently drawing about 8,000 visitors a month. That number continues to increase as word gets out, and should gain even more traction as NREL continues improving the Portal’s functionality. Recently, the Portal team unveiled a visual patent finder, based on a Pacific Northwest National Laboratory (PNNL) technology. The PNNL tool allows users to expand their quest to find technology beyond simple keyword searches. Users can now click on a technology category of interest and narrow their search to the patent that best suits their business needs.

These technologies are not the leftovers in the basement bargain bins, either, as the site lists many promising discoveries. As an added benefit, even if some of the innovations become licensed for one usage, there can be variations that allow new partners to try different commercial ventures with the same property.

As an indicator of its emerging prominence, non-DOE partners have also signed on to showcase their patented developments. Among those are the:

- Battelle Memorial Institute
- Colorado School of Mines
- Great Lakes Bioenergy Research Center
- NASA
- Naval Research Laboratory
- University of Colorado.

NASA, which became a partner after Ringer approached them, appreciated getting hits on its renewable energy patents, and soon decided to open its own portal based on the Portal.

“The fact that NASA took [the Portal architecture] for its own speaks volumes,” Ringer said. There’s another added benefit. As the site gains prominence, the intragovernmental collaboration is a sign of efficient government spending, Farris said.

To drive home the idea that this site belongs to all labs, the design team worked to ensure that it in no way appears NREL-centric to visitors. Farris, who has shepherded the concept, is loath to be referred to as the “mastermind” of the Energy Innovation Portal. Instead, “it’s all about getting visibility for the technologies,” he explained. He expects continued EERE support for NREL to grow the Portal, which in turn should increase the number of tech transfers. Clearly, these days, there’s nothing wrong with being tech transfer’s Craigslist.

—Ernie Tucker

Air Conditioner Ready to Change Industry

Award-winning air-conditioning cycle cools with a fraction of air conditioner's energy.

When National Renewable Energy Laboratory (NREL) scientist Eric Kozubal began pondering an evaporative and desiccant cooling system in 2006, the concept wasn't new. After all, desiccants are used to create very dry air, ideal for cooling with evaporative techniques. Desiccants, which can be liquids or solids, had been deployed in heat-exchange cooling systems before. There were, however, limits to their effectiveness.

In looking for something better, Kozubal envisioned combining desiccant and evaporative cooling into an innovative "cooling core." This would marry the desiccants' capacity to create dry air using heat and evaporative coolers' capability to turn dry air into cold air. If it worked, it could be nearly twice as efficient as conventional heating, ventilation, and air conditioning (HVAC) systems. However, the path to achieving this wasn't clear cut.

Kozubal, who was joined on the quest by Jason Woods and Jay Burch under program manager Ron Judkoff, noted significant challenges.

"What we thought was far removed from what it evolved into," Kozubal said.

Judkoff added, "We'd investigated evaporative and desiccant cooling technologies for many years, but could not find a way to combine them in a cost-effective manner. The recent availability of new materials, and the creativity of our researchers resulted in a major breakthrough with great potential for the future."

The researchers found out that they couldn't just use off-the-shelf components to build the technology they envisioned. In addition, they discovered that they needed to use liquid desiccants in close contact with the airflow in the cooling system. This need created problems in early desiccant systems, however.

NREL engineers Jason Woods and Eric Kozubal conduct research on a DEVAP prototype at the HVAC Systems Laboratory.

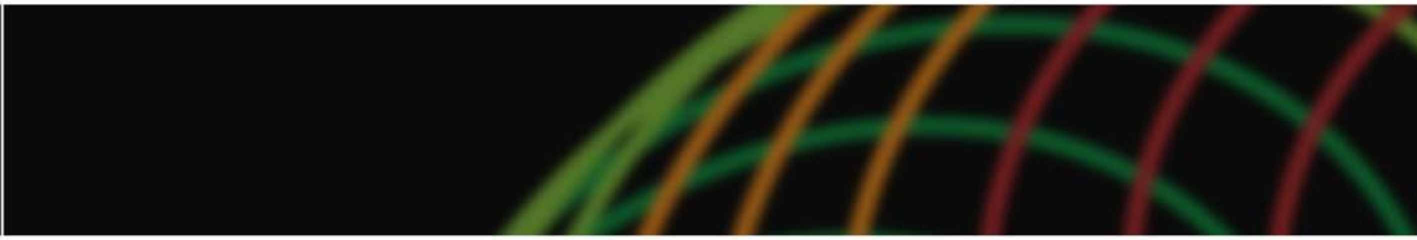
The first desiccant systems were plagued by a problem called "carry-over," in which desiccants can get into the airflow and corrode the rest of an HVAC system's ductwork and components. Kozubal said that they needed to find a way to create positive separation between desiccant and air. This led to the invention of an air conditioner that uses an innovative membrane that is permeable to water vapor, but not the liquid desiccant.

Proof-of-Concept Shows Potential for Every Climate

In early 2008, NREL constructed a proof-of-concept prototype and showed that the air conditioning cycle worked as expected and could be built using inexpensive materials. Unlike an evaporative cooler, which is only effective in dry climates, the Desiccant-Enhanced Evaporative (DEVAP) Air-Conditioning Cycle approach could function in any location.

Encouraged, the research team followed the path to full-scale development of the invention. NREL partnered with two industry experts, AIL Research and Synapse Product Development, who would help construct the two proof-of-performance prototypes. By the end of 2011, they had successfully built the working demo models and written a report that garnered industry interest.

Unlike energy-intensive conventional systems, DEVAP requires neither a compressor nor environmentally harmful refrigerants, but instead



uses a liquid desiccant cycle that removes humidity from the air, then uses thermal heat to evaporate water out of the desiccant in a component called a regenerator. Thus, energy is expended only to dehumidify the air, while evaporative cooling further amplifies the cooling effect.

The researchers expect that natural gas will provide the energy in most cases; however, DEVAP can also be integrated with solar and waste heat. The design eliminates much of the electricity needed to power a conventional air conditioner, because only fans and small liquid pumps are needed. As a result, a DEVAP air conditioner is expected to use 30% to 80% less energy than top-of-the-line refrigeration-based air conditioning.

"We're still evolving the idea," Kozubal said, with "a lot of science to make it smaller and cheaper."

The next phase, he explained, is to continue to refine the components to reduce size and cost. The next step for this project will be to build it into a prototype that will demonstrate a marketable air conditioner design. This could take another several years. Once completed, Kozubal expects the first application would be in the commercial cooling market, which has packaged air conditioners that will be easy to retrofit or replace with new technology. Residential cooling would certainly follow.

A Disruptive Technology in the Making

Kozubal sees DEVAP becoming a popular choice because of the likely savings in energy costs. These are key, because air conditioning currently consumes about 15% of the electricity generated in the United States and is a major contributor to peak electrical demand on hot summer days.

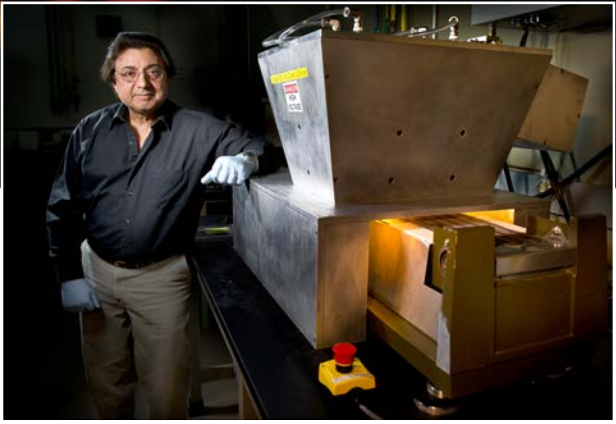
DEVAP has other benefits, including:

- Removing harmful refrigerants, which have a far greater global warming potential than CO_2
- Better temperature and humidity control than standard AC because DEVAP treats each separately and effectively
- Better indoor air quality, because vast ventilation air is inherent in the DEVAP AC cooling cycle—gone will be the days of stuffy homes and sleepy co-workers.

"It could be a disruptive technology," he said, to describe this innovation that is poised to revolutionize embedded concepts about energy costs and consumption. And during times of heavy electricity use, that kind of disruption is welcome.

—Ernie Tucker

Shining a New Light on Silicon PV Manufacturing



Bhushan Sopori stands next to a prototype of the novel furnace that eliminates defective wafers before they enter cell and module production lines.

Groundbreaking furnace tests photovoltaic wafer viability.

"It's all very complicated," says Principal Scientist Bhushan Sopori, "but what matters is that we're controlling, shaping light." While the National Renewable Energy Laboratory's (NREL) light-shaping innovation is indeed complicated, it actually simplifies the process of fabricating silicon solar wafers. It does this by creating just the right conditions for something to go wrong... acting almost like a time machine that predicts if something will go wrong in the future.

Leaning against a metal furnace that, despite containing a high degree of thermal heat, remains cool to the touch, Sopori describes its efficiency. "Almost none of the light is wasted. It is all directed precisely to the surface of the moving wafer."

The furnace, which directs a stationary beam of light across the surface of the wafer as a conveyor belt carries it through an illumination zone, appears to be a means of inspecting the surface of these very thin wafers for defects. However, silicon wafers have rough surfaces, covered with irregularities that would hide most fatal defects, even when viewed under the most sophisticated lens.

The sound of a gentle snap comes from inside the illumination zone and a broken wafer moves out from beneath the metallic structure. For the sake of the demonstration, the wafers are supported by an extra surface—otherwise, the broken pieces would fall through the metal rods on the belt, which would automatically eliminate them from the line.

"This was a wafer we just scratched," Sopori notes, showing the damaged wafer. He then demonstrates how he can adjust the attached computer interface to apply all the different parameters of thermal stress.

Meanwhile, the conveyer belt carries a second wafer through the other side of the furnace, unscathed.

"This wafer, on the other hand, had no damage. It will stay in the production line to undergo the next cell fabrication steps."

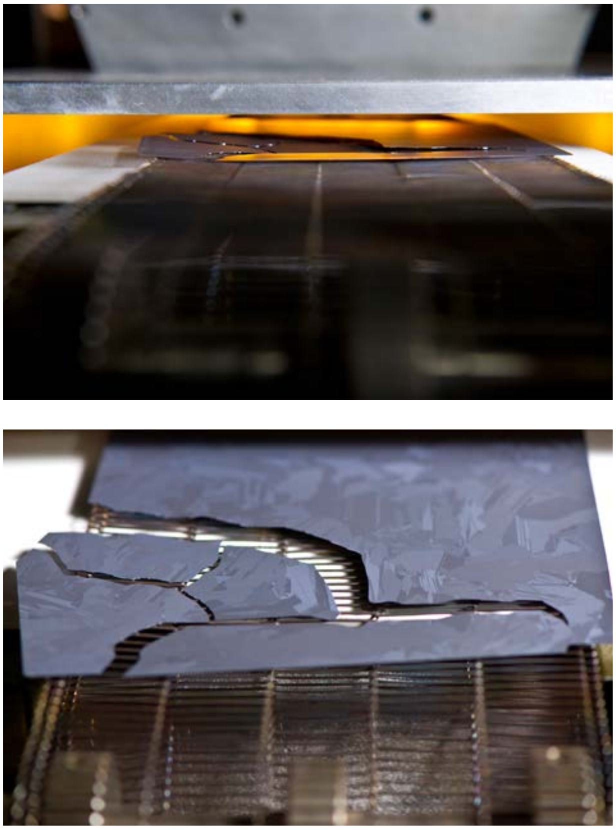
Sopori explains that the test is unique because the scratched wafer was broken, but the undamaged wafer was not—and not only that, the test doesn't alter or weaken an undamaged wafer in any way.

Tackling the Serious Issue of Wafer Breakage

The silicon photovoltaic (Si-PV) wafer screening system was designed to solve a serious problem in the silicon wafer manufacturing industry, which comprises 85% of the PV cell market. Typically, between 5% to 10% of wafers break during the process of cell production, a material loss that limits production yields and increases the final cost of PV modules.

"We have been selling furnaces to the semiconductor industry for the last 30 years," said Jim Smith, the business development manager of Tystar Corporation, "and we consider the wafer screening tool to be a very low-cost solution to the wafer breakage problem in the solar industry."

Manufacturers are using increasingly thin wafers to achieve higher cell efficiency and to lower the wafer



Intense light energy (top) heats portions of the wafer, producing a predetermined stress distribution that will break wafers with fatal defects, such as microcracks. The broken wafers (bottom) exit the system and can be automatically eliminated

cost. Unlike the microelectronics industry, which polishes the surface of silicon cells to remove the surface damage and microcracks that can occur during wafer sawing, the PV industry does not prepare wafers in a way that maintains their mechanical strength.

Deceptively simple in appearance, the system reflects decades of research in optical physics, materials research, and fracture mechanics. It has attracted a licensing partner, AOS Solar—a company that is working with solar cell and wafer manufacturers that have purchased test systems for evaluation.

Synergies Among Innovative Technologies Solve Big Industry Problems

It's quite a feat when a new technology can change an entire manufacturing process, but even more so when it can be coupled with other innovations to solve new and expansive problems. In 2011, NREL and AOS Solar earned an R&D 100 Award from R&D Magazine, recognizing the Optical Cavity Furnace (OCF) as one of the top innovations of the year. The system performs a full array of processing steps including junction formation, annealing, metallization, and oxidation.

When developing the Si-PV wafer screening system, Sopori and his team employed basic optical principles of the OCF to provide a light source for an optical concentrator and harnessed optical excitation in a completely new way to produce very high efficiency.

Because solar wafers have rough surfaces, the team members couldn't use conventional optical software to calculate the thermal stresses required for testing silicon wafers in a moving system. Instead, they needed to build a detailed model to demonstrate essential physical processes such as light reflection and absorption as a function of temperature, surface conditions, and wafer thickness. To solve the R&D challenge, researchers derived the needed information using NREL's R&D 100 Award-winning PV Optics software. Using the software in conjunction with thermal modeling, they extended the software's capability to evaluate silicon wafers' emissivity, or heat-transmitting properties.

It has also earned support among leaders in the research community and industry.

During its development, researchers engineered the system to replicate the stresses imposed that can occur during solar cell processing: oxidation, annealing, metallization, diffusion, and wafer handling, all of which can cause existing defects to propagate and lead to wafer breakage. By creating stress equal to what has been measured in cell and module production, the test is much more accurate than methods that depend on inspection or representative sampling.

The system works by applying a non-uniform thermal profile to the wafer as it moves through the illumination zone, producing a dynamic stress distribution across the wafer's surface. If any defects are present in the wafer, they serve as stress concentrators and crack nucleation spots. As the dynamic stress is applied, it tends to intersect and widen the cracks, causing the wafer to break. Because the stress is highest at the defects, or nucleation spots, the rest of the wafer is not subject to enough stress to impose new damage.

The technique is not only accurate, but also efficient. It requires less than 0.002 kilowatt-hours (kWh) of optical energy per wafer and costs less than $0.02/wafer—an expense that has a negligible effect on the levelized cost of energy. Beyond these benefits, one of the most exciting advantages is its flexibility.

"We have designed this system to be integrated easily into existing PV manufacturing processes," Sopori says. "It is compatible with existing conveyor belt technology and can be integrated into the manufacturing lines—and because the parameters are adjustable, it can accommodate manufacturing changes that come in the future."

— Molly Riddell

Rene Rivero, a post-doc researcher at NREL, positions a silicon wafer for testing in the furnace.

Solar Accuracy to the 3/10000 Degree

Revolutionary calibration technique carries world standard.

Say the word "pedigree" and most people think thoroughbred horses or purebred puppies. However, a metrologist such as the National Renewable Energy Laboratory's (NREL) Senior Scientist and Metrology Laboratory Manager Ibrahim Reda thinks calibration traceability to national and international standards. Quality research requires, among many things: accuracy, repeatability, defensibility, and calibration traceability. Calibration traceability is research data's pedigree. The data have more value because you can validate the origin and you can predict its future accuracy with greater confidence.

Defining the Broadband Outdoor Radiometer Calibration Process

The NREL Metrology Laboratory, which is located at the Solar Radiation Research Laboratory, developed a process called Broadband Outdoor Radiometer Calibration. Chet Wells, Daryl Myers, and Tom Stoffel started this process in the late 1970s to calibrate radiometers, such as pyranometers and pyrheliometers, which measure the sun's energy. Radiometers are utilized across the globe for a variety of purposes including:

- Photovoltaic (PV) research on solar cell efficiency: evaluating how a particular cell performs under certain atmospheric conditions
- Atmospheric science: predicting weather and advancing international and regional climate simulations and projections
- Agriculture: advancing knowledge of photosynthesis and its effect on crop production
- Solar resource data: determining if a parcel of land is more suitable for a PV field or soybeans
- Renewable energy applications: determining current and future development and investment.

Considering the numbers of radiometers in use around the world, and the copious amounts of solar data they generate for the specific purpose of making fiscal decisions, it becomes ever more critical to ensure a world standard in instrument accuracy, precision, and calibration traceability.

Ibrahim Reda works at NREL's Solar Radiation Research Laboratory, where he has developed Solar Position Algorithm software.

Position of Sun: Accuracy to the 3/10000 Degree

Ibrahim Reda pioneered an algorithm that tracks the position of the sun to within 0.0003 degrees of accuracy through the year 6000. Now that's accuracy!

Measurement accuracy is critical to our smart grid future. "The smart grid has to know precisely what your budget is for each resource you are using — oil, coal, solar, wind. Accuracy is translated into dollars; more accurate is more attractive and less risky to investors," explained Ibrahim Reda.

"We characterize the instruments based on the solar angle," Reda said. "It's vital that instruments get a precise read on the amount of energy they are getting from the sun at a precise solar angle."

The process, which has been accredited under the International Organization for Standardization (ISO) 17025, adds unique value for NREL, other national laboratories, industry, and academic partners because it validates the lab's solar measurements, and stands as proof that they conform to international standards. By reducing uncertainty, validating calibration traceability, and using an accredited world-standard process, NREL increases stakeholder confidence in the bankability of its data and research results.

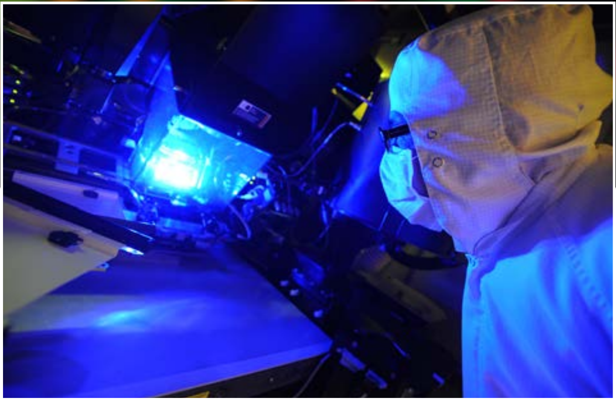
NREL Delivers World-Class Solar Measurements

NREL is the only institution in the world that currently provides ISO 17025-accredited radiometer calibrations that are traceable to the World Radiometric Reference (WRR)—calibrations that feature both unmatched characterization versus sun angle range as well as low uncertainty. The WRR, which is the international standard from which all radiometer calibrations are traceable, is maintained by the World Meteorological Organization in Switzerland, and is transferred to the world's scientific community once every five years during the International Pyrheliometer Comparisons gathering in Davos. Ibrahim Reda and Tom Stoffel regularly participate in this outdoor calibration exercise to ensure that NREL's calibration standards are directly traceable to the WRR. Their efforts in guaranteeing NREL's radiometer calibrations and solar energy measurements help the laboratory maintain its world-class pedigree.

—Leigh Ramsey

Ibrahim Reda installs reference radiometers to perform the annual NREL-Pyrheliometer Comparison (NPC), on the deck of NREL's Solar Radiation Research Laboratory.

Two New R&D 100 Awards Uphold NREL Winning Streak



Solar Junction's SJ3 solar cell is based on NREL's pioneering multijunction work. The large photo shows the molecular-beam epitaxy (MBE) deposition system, and the inset is the completed SJ3 wafer.

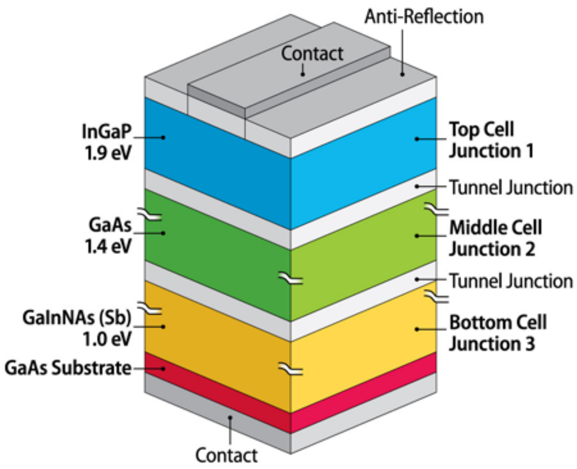
Solar cell and cooling technology solve industry problems.

In 2012, the National Renewable Energy Laboratory (NREL) developed technologies that earned two R&D 100 awards—bringing the total to 52 since 1984. The lab collected trophies for a record-setting, high-efficiency solar cell and a cost-slashing air conditioning technology. These achievements underscore the lab's leadership among national laboratories in renewable energy and energy efficiency research.

This year, NREL and its corporate partners won R&D awards for the following technologies.

SJ3 Concentrator Solar Cell

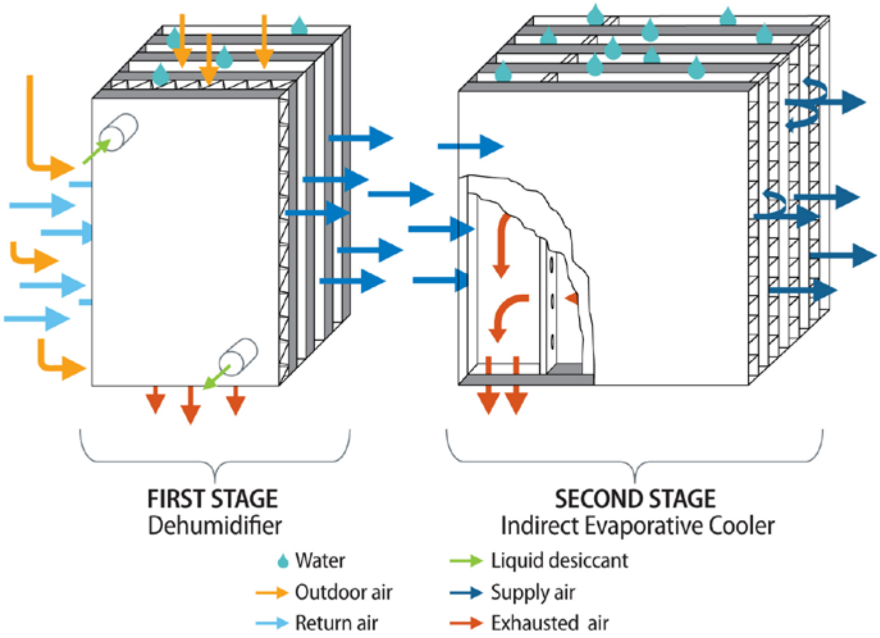
Problem: Even though multijunction solar cells have higher conversion efficiencies than any other type of solar cell, developers of utility-scale and space applications need cells that are both more efficient and lower in cost to be cost-effective and meet the demand for power.



A schematic of the SJ3 multijunction cell highlights the three junctions and their chemical compositions and bandgaps (in electron-volts). The top cell uses the high-energy end of the solar spectrum, and lower cells use correspondingly lower-energy portions of the spectrum.

Solution: NREL, in partnership with Solar Junction, a manufacturer of high efficiency multijunction cells for the concentrated photovoltaic (CPV) market, developed this award-winning technology. Working together, researchers discovered a material that could be used for a bottom junction and that has an optimal bandgap and lattice constant—dilute-nitride alloys incorporating gallium, indium, nitrogen, and arsenic (GaInNAs). The team also used molecular-beam epitaxy (MBE), a manufacturing technique used in the cell phone and solid-state lighting industries, to grow high-performance multijunction cells cost-effectively.

Considered "the Oscars of Innovation," the R&D 100 Awards have been presented each year since 1963. Through the awards, R&D Magazine identifies and recognizes revolutionary technologies recently introduced to the market. The magazine editors and a panel of technical consultants, university faculty, and industrial researchers evaluate numerous nominated technologies to select the top 100 based on their potential impact. Past award winners have included the flashcube (1965), halogen lamp (1974), liquid-crystal display (1980), anticancer drug Taxol (1993), and HDTV (1998).



DEVAP consists of two distinct stages: a dehumidifier stage and an indirect evaporative cooling stage.

Impact: The SJ3 solar cell has the highest efficiency ever—43.5% at 418 suns—yet a comparable cost. It uses a lattice-matched multijunction architecture that has a near-term potential of developing cells that will approach 50% efficiency. A schematic of the SJ3 multijunction cell highlights the three junctions and their chemical compositions and bandgaps (in electron-volts). The top cell uses the high-energy end of the solar spectrum, and lower cells use correspondingly lower-energy portions of the spectrum.

Desiccant-Enhanced Evaporative (DEVAP) Air Conditioner

Problem: Air conditioning currently consumes about 15% of the electricity generated in the United States. It is also a major contributor to peak electrical demand on hot summer days, which can lead to escalating power costs, brownouts, and rolling blackouts.

Solution: NREL and its partners, AILR Research, Inc. and Synapse Product Development LLC, combined desiccant-based dehumidification with indirect evaporative cooling to invent the DEVAP air conditioner.

Impact: Estimates show that the DEVAP air conditioner provides superior comfort for commercial buildings. This technology works in any climate at a fraction of the energy costs of conventional air-conditioning equipment, releasing far less carbon dioxide and cutting costly peak electrical demand by nearly 80%. Widespread use of this technology could save billions of dollars in investments and operating costs for our nation's electrical utilities and their customers.

—Karen Atkison

About

Continuum Magazine is NREL's quarterly publication that showcases the laboratory's latest and most impactful clean energy innovations and the researchers and unique facilities that make it all happen.

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NREL has a history of success in scientific discovery and developing innovative technologies to meet the challenges of a clean-energy future. As the only U.S. national laboratory singularly focused on advancing renewable energy and energy efficiency, NREL's mission spans the spectrum of clean energy solutions—including pioneering research in solar, wind, biomass, hydrogen, and geothermal energy. With 35 years of successful innovation from fundamental research and analysis through commercializing and deploying energy efficiency and renewable energy solutions, NREL continues to pave the way toward a clean energy transformation.

To learn more about NREL's 35 years of successful innovation, please visit **http://www.nrel.gov/about/accomplishments.html**

For *Continuum Magazine* online, please visit **http://www.nrel.gov/continuum/spectrum/**

NATIONAL RENEWABLE ENERGY LABORATORY

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